

Final Report

In-situ and Remote Sensing Measurements in Support of the EOS/MODIS Retrieval Algorithm Validation Program

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This report documents the work conducted through NASA EOS grant S-97894-F, *In-situ and Remote Sensing Measurements in Support of the EOS/MODIS Retrieval Algorithm Validation Program* to the National Center for Atmospheric Research. Andrew Heymsfield was the Principal Investigator, and Co-Investigators and Collaborators included Larry Miloshevich (NCAR), Sergey Matrosov (CERES/NOAA), Greg McFarquhar (NCAR/University of Illinois), Bryan Baum (NASA Langley), Ping Yang (Texas A & M), Shaima Nasiri (University of Wisconsin), and Sarah Thomas (University of Wisconsin). We wish to thank the EOS project for allowing us to collect and analyze several excellent sets of microphysical data and to provide us with funding to publish our results in several meteorological journals.

In the discussion below, we will first summarize the work we initially proposed to conduct under this grant. Some of the highlights of the research will then be identified, the field programs we were involved in will be discussed, and journal articles describing the research we conducted through this grant will be listed.

In our original proposal, the following tasks that we proposed to conduct were identified. “*We will collect in situ aircraft measurements of crucial cloud microphysical and extinction properties during a series of planned EOS validation experiments, then use these measurements to develop, improve and validate several independent retrieval techniques from radar, infrared radiometer and lidar measurements, allowing us to derive vertical profiles of effective radius (r_e) and the visible extinction coefficient (from which cloud optical depth (τ) is derived, for comparison to retrievals of these properties from collocated MAS or MODIS radiance measurements. The in situ aircraft measurements upon which the remote sensor retrievals of r_e and will be based use a unique complement of instrumentation that*

includes a direct measurement of τ and encompasses the radiatively-important small particle portion of the size distribution. Our data products will also be available for evaluation of cloud retrieval algorithms from other EOS sensor measurements that will be acquired in coordination with the MODIS validation effort, particularly the Multi-angle Imaging Spectroradiometer (MISR), the Clouds and the Earth's Radiant Energy System (CERES) instrument, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)."

"We will participate in the MODIS validation campaigns to be conducted at the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) site in September 1998 and April/May 1999, where we will mount our microphysical probes on the University of North Dakota (UND) Citation (or other research aircraft), and on the NCAR C-130 aircraft during the FIRE-III Arctic experiment (SHEBA). We will also apply our techniques for deriving τ and r_e to similar in situ data we acquired and have been analyzing from the NASA Subsonic Aircraft Contrail and Cloud Effects Special Study (SUCCESS) experiment, for cases in which colocated MAS data from the ER-2 are available. Collocated radar, radiometer, lidar, sun photometer, and MAS or MODIS data were/will be available for all these experiments."

During March 2000, our EOS funding allowed us to install and operate a Cloud Particle Imager (CPI) probe on the University of North Dakota Citation aircraft. The Citation participated in the ARM 2000 IOP. We collected a set of data that led to some crucial advances in the areas of cloud and climate modeling, retrievals of cloud properties of satellite and ground-based remote sensors, and parameterization development. A description of the findings in the articles that use this data set is given below.

Paper I: Heymsfield, A. J., A. Bansemer, S. Lewis, J. Iaquinta, M. Kajikawa, C. Twohy, M. R. Poellot, and L. M. Miloshevich, 2002. A General Approach for Deriving the Properties of Cirrus and Stratiform Ice Cloud Particles, *J. Atmos. Sci.*, **59**, 3--29.

In this article, a new method for calculating ice particle mass and ice water content from in-situ probe data was developed. The approach uses particle area to derive mass and provides a self-consistent means of relating ice water content to extinction. The technique was validated using ARM 2000 measurements of the ice water content. New relationships were developed to

calculate ice particle mass, terminal velocity and indirectly the cloud effective radius.

Paper II: Nasiri, Shaima L., Bryan A. Baum, Andrew J. Heymsfield Ping Yang, Michael R. Poellot, David P. Kratz, and Yongxiang Hu, 2002: The Development of Midlatitude Cirrus Models for MODIS Using FIRE-I, FIRE-II, and ARM In-Situ Data, *J. Appl. Meteor.*, **41**, 197--217.

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While detailed in-situ data from cirrus clouds have been collected during dedicated field campaigns, the use of the size and habit distribution data has been lagging in the development of more realistic cirrus scattering models. In this study, we examine the use of in-situ cirrus data collected during three field campaigns to develop more complex midlatitude cirrus microphysical models. Data are used from the FIRE-I (1986) and FIRE-II (1991) campaigns (FIRE refers to the First ISCCP Regional Experiment; ISCCP refers to the International Satellite Cloud Climatology Project) and a recent ARM (Atmospheric Radiation Measurement) campaign held in March-April, 2000. The microphysical models are based on measured vertical distributions of both particle size and particle habit, and are used to develop new scattering models for a suite of MODIS bands spanning visible, near-infrared, and infrared wavelengths. The sensitivity of the resulting scattering properties to the underlying assumptions of the assumed particle size and habit distributions is examined. We find that the near-infrared bands are sensitive not only to the discretization of the size distribution, but also to the assumed habit distribution. Additionally, our results indicate that the effective diameter calculated from a given size distribution tends to be sensitive to the number of size bins that are used to discretize the data, and also to the ice crystal habit distribution.

Paper III: Heymsfield, A. J., and L. M. Miloshevich, 2003: Parameterizations for the cross-sectional area and extinction of cirrus and stratiform ice cloud particles. *J. Atmos. Sci.*, in press.

This study presents observational data that are used to relate the cross-sectional area of an ice particle to its maximum diameter (D), for a number of individual particle habits and for natural mixed-habit populations of ice particles in mid-latitude, continental, synoptically generated cirrus clouds. The cross-sectional area is expressed in terms of the shape-sensitive parameter "area ratio" (A_r , the ratio of a particle's projected cross-sectional area to the area of a circle having the particle's maximum diameter). The

$A_r(D)$ relationships for cirrus clouds were derived from CPI, 2D-C, and 2D-P data during slow Lagrangian spiral descents, and from balloon-borne ice crystal replicator data. The dependence of the coefficients of the $A_r(D)$ relationship on height within the vertical cloud column was examined and related to microphysical processes operating in the clouds. The area ratio was found to decrease systematically with increasing particle diameter for most individual particle habits and for natural cirrus cloud populations.

Paper IV: Heymsfield, A. J., S. Matrosov, and B. Baum, 2003: Ice Water Path--Optical Depth Relationships for Cirrus and Deep Stratiform Ice Cloud Layers. *J. Appl. Meteor.*, conditionally accepted for publication.

Particle size distribution (PSD) and particle shape information collected during Lagrangian spiral descents through 13 midlatitude and 6 tropical ice clouds are analyzed to investigate the relationship between cloud optical depth in visible wavelengths (τ_v) and the ice water path (IWP). We explore and develop quantitative relationships between τ_v and IWP that depend on the cloud thickness, the mid-cloud temperature, the slope of the particle size distribution, the median mass diameter, and the effective radius. The underlying of these relationships is the dependence of the slope of the particle size distribution on cloud temperature and cloud thickness. The slope of the particle size distribution tends to decrease with increasing cloud depth (beginning from cloud top) and increasing temperature. This tendency towards a flatter spectral slope with increasing penetration into the cloud layer leads to a monotonic decrease in the extinction coefficient relative to the ice water content downward from cloud top to base.

We completed several studies that did not depend on the use of data from the ARM 2000 field program. These include the following papers.

Paper V: Matrosov, S. Y., and A. J. Heymsfield, 2000: The use of Doppler radar measurements to derive ice cloud particle fall velocity relations for climate models. *J. Geophys. Res.*, **105**, 22,427--22,436.

Knowledge of the rate of fall of cirrus crystals is important for an adequate representation of ice clouds in general circulation models and for retrieval of ice cloud properties from remote sensors. This study developed a new approach for retrieving several properties of cirrus ice crystal populations, using remote sensing data from a vertically pointing Doppler radar and an infrared radiometer.

Paper VI: Yang, P., B.-C. Gao, B. Baum, W. Wiscombe, Y. Hu, S. Nasiri, P. Soulen, A. Heymsfield, G. McFarquhar, L. Miloshevich, 2001. Sensitivity of cirrus bidirectional reflectance at MODIS bands to vertical inhomogeneity of ice crystal habits and size distributions. *J. Geophys. Res.*, **106**, D15, 17,267-17,291.

Using our balloon-borne vertical profiles of particle size distributions in mid-latitude cirrus, this study shows that a “three layer” model of cirrus clouds accounts for the radiances of cirrus clouds much more reliably than a one-layer model that considers particle size distributions to be homogeneous throughout a cirrus layer. The cloud layers were set up so that the uppermost layer contained more small particles than the lowest layer. The near-infrared radiances were found to be most sensitive to the presence of small particles near cloud top, and this will affect retrievals using radiances measured at NIR wavelengths such as 1.64 microns. This research also indicates that the shape of the small particles will have an influence on the ice cloud particle size retrievals performed by MODIS.

Paper VII: Buschmann, N., G. M. McFarquhar and A. J. Heymsfield, 2002: Effects of observed horizontal inhomogeneities within cirrus clouds on solar radiative transfer. *J. Geophys. Res.*, in press.

In situ microphysical and combined radar and radiometer measurements of 11 cirrus clouds from Central Equatorial Pacific Experiment (CEPEX), European Cloud and Radiation Experiment (EUCREX), investigation of Clouds by Ground-Based and Airborne Radar and Lidar (CARL), and First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) are used to investigate effects of horizontal cloud inhomogeneities on solar radiative transfer. A three-dimensional ray-tracing model (GRIMALDI), based on the Monte Carlo method, is used to calculate upward and downward flux densities and absorption for the spectral range from 0.38 to 4.0 μm . Radiative flux densities are calculated using the inhomogeneous clouds derived from the observations and for horizontally and vertically averaged homogeneous clouds. Horizontally averaged values of radiative flux densities and absorption for heterogeneous clouds can differ by up to 30% from those calculated for the homogeneous clouds for convectively induced tropical cirrus clouds. The midlatitude cases examined tended to be more homogeneous, and hence differences between radiative properties for the homogeneous and heterogeneous clouds did not exceed

10%. For cirrus clouds with mean optical thicknesses smaller than 5 and with relative variances of optical thickness smaller than 0.2, errors caused by the homogeneous assumption are smaller than $\pm 10\%$.

In addition to the journal articles noted above, we have prepared more than a half-dozen conference papers that have been presented at two conferences on Cloud Physics and two conferences on Radiation. Andrew Heymsfield, Larry Miloshevich, Shaima Nasiri, and Sarah Thomas have presented the papers.

A major focus of our efforts throughout the funding period was the development of a cirrus cloud microphysical database for use by EOS investigators to conduct radiative transfer calculations of cirrus cloud properties. The work on this database began during 1999, when the MODIS Remote Sensing of Cirrus Clouds Working Group (http://arm1.ssec.wisc.edu/~shaima/cirrus_group.html) was formed by Andrew Heymsfield (NCAR), Bryan Baum of NASA/Langley and Shaima Nasiri of the University of Wisconsin to foster the development of radiative transfer algorithms to retrieve ice cloud properties from MODIS.

As part of this effort, we at NCAR produced cirrus particle size distributions and particle imagery from ascents of a balloon-borne ice crystal replicator data for three FIRE II cases: 25 November, 5 December, and 26 November 1991. Our data set is located at <http://box.mmm.ucar.edu/science/cirrus/>. In addition, we have added detailed particle size distributions and particle habit data from the midlatitude observations from FIRE-I and the ARM IOP, and from tropical observations in connection with the Tropical Rain Measuring Missions (TRMM) validation field campaigns.

Judging from the content of our published work and the number of publications, we believe that we have accomplished what we have initially proposed to do through our EOS funding, and have productively used our funding to promote the goals of the EOS program. We are indebted to the EOS program for allowing us to conduct this research.